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SUBISOKINETIC SAMPLING ERRORS FOR AIRCRAFT TURBINE ENGINE SMOKE--ETC(U)
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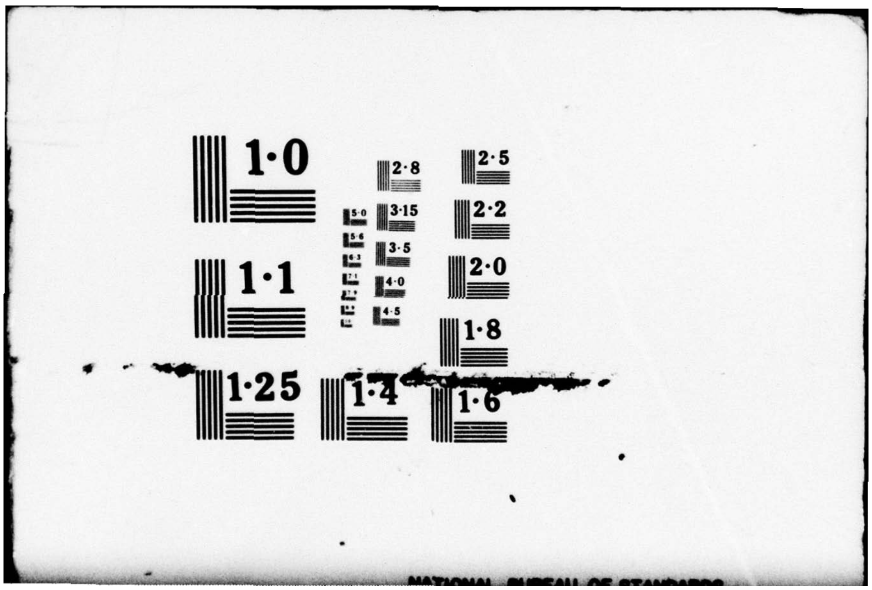
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SUBISOKINETIC SAMPLING ERRORS FOR AIRCRAFT TURBINE ENGINE SMOKE PROBES

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Experimental evidence that isokinetic sampling can be important for submicrometer particles in high speed flows was presented in CEEDO-TR-77-48. This report applies those results to gas turbine engine smoke measurement. The analysis predicts a 15 to 30 percent subisokinetic sampling error at a take-off engine power setting. It is concluded that subisokinetic errors do not greatly affect smoke number determinations but should be considered when true smoke density is measured.

PREFACE

This report summarizes work done between 15 September 1977 and 15 January 1978. Joseph A. Martone, Capt, USAF, BSC, was the project engineer and principal investigator. The work is an application of experimental results published previously in CEEDO-TR-77-48. Support was provided by the Environics Directorate, Detachment 1 (CEEDO) ADTC, Tyndall AFB, Florida.

This report has been reviewed by the Information Office (OI) and is releasable to the National Technical Information Service (NTIS). At NTIS it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

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INTRODUCTION

The Environmental Protection Agency (EPA) has promulgated emission standards and measurement procedures for smoke produced by aircraft turbine engines[1]. Smoke, by EPA definition[1], is particulate matter in engine exhaust that obscures transmission of light. The EPA test methods are largely adoptations of the Aerospace Recommended Practice, ARP 1179, developed by the Society of Automotive Engineers (SAE) Committee on Aircraft Exhaust Emissions Measurement (E-31).[2] The procedure involves passing a known mass of engine exhaust gas through a filter and measuring the optical reflectivity of the collected particles. Dividing this result by the clean filter reflectance yields a dimensionless term used for quantifying aircraft engine smoke emissions called smoke number (SN) according to the following equation:

$$SN = 100 \left[1 - (R_s/R_w)\right] \qquad (1)$$

R_s = sample reflectance

R_w = clean filter reflectance

ARP 1179 specifies a sample flow rate of 286 cm^3/s using a single element sampling probe with an inlet diameter (D_p) of 2.0 mm. This means that a typical smoke probe located at the exit nozzle of an aircraft engine operates at about 20 to 33 percent of the isokinetic sampling velocity[3]. Using this information and the findings of Martone et al[4], it is possible to estimate subisokinetic sampling errors associated with smoke probe operation. It should be noted that the EPA procedure[1] permits multipoint manifolded sampling probes with no specification for their physical dimensions, thus the entrance velocity at each orifice could be appreciably different from the velocity at the inlet of a single element smoke probe.

SECTION II

BACKGROUND

The study conducted by Martone et al[4] used small bore aspirated probes to obtain samples of submicrometer particles suspended in unheated near sonic and supersonic free jets. Subisokinetic sampling errors were determined for free jet velocities of Mach 0.6, 0.8, 1.26, and 1.47. For particle-nozzle Stokes numbers (K) between 0.10 and 0.14 it was concluded that the ratio of the sampled aerosol concentration to true free stream aerosol concentration (C/C_o) is given by:

$$C/C_o = 0.69 + 0.31\ (U_o/U) \pm 12\% \qquad (2)$$

where:

K = Stokes number of the particle-nozzle system = $\rho_p d_p^2 U_o C_s / 18\mu_g D_p$.

ρ_p = particle density.

d_p = particle diameter.

μ_g = gas viscosity.

C_s = Cunningham slip-flow correction.

U_o = ambient flow velocity along the flow line passing through the axis of the probe; for supersonic flows it is the subsonic velocity which exists immediately downstream of a probe bow shock.

U = mean flow velocity at probe inlet.

D_p = diameter of sampling probe inlet.

C = aerosol concentration of sample (mass/volume).

C_o = aerosol concentration of free stream (mass/volume).

Subisokinetic sampling errors predicted from Eq. (2) are in good agreement with results reported by Davies[5], Belyaev and Levin[6], and Zenker as reported by Fuchs[7] (Figure 1). Even though these investigators[5-7] used particles greater than 4 μm diameter, large bore probes and low speed flows, their studies included Stokes numbers near 0.1. For example, Zenker[7] sampled vertical air streams containing spherical glass beads or limestone dust with particle diameters from 7 to 73 micrometers. For Stokes numbers between 0.06 and 14 and values of U/U_o between 0.4 and 2.5, Zenker[7] provides the following relationship:

$$C/C_o = N + (U_o/U)\ (1-N) \qquad (3)$$

where:

N = dimensionless coefficient depending only on the Stokes number

For Stokes numbers less than 0.5 a least squares fit (N vs $K^{1/2}$) to Zenker's[7] smoothed data gives:

$$N = 1.02 - 0.85\ (K)^{1/2} \qquad (4)$$

r^2 = coefficient of determination = 0.99

The good agreement between Eqs. (2) and (3) demonstrates the usefulness of both expressions for predicting sonic range subisokinetic sampling errors. Since Eq (3) was experimentally verified over a wider range of Stokes numbers, it will be used in the following calculations to estimate subisokinetic errors associated with gas turbine engine smoke probe operation.

SECTION III

CALCULATION OF ANISOKINETIC ERRORS

To apply the Zenker equation (Eq (3)) the first step is to calculate appropriate particle-nozzle Stokes numbers. This requires a knowledge of engine exhaust temperature and velocity as well as information about the exit plane particle size distribution. For illustrative purposes, consider the JT9D turbofan engine which powers the Boeing 747 aircraft. According to the LAAPCD[8], at the take-off power setting the JT9D has an exhaust temperature of approximately 480^{o}C and an exhaust velocity (U_o) near 400 m/s (Mach 0.74). Although the size distribution of particles in a gas turbine engine exhaust is not known with much certainty, the result of the often cited work of Stockham and Betz[9] will be used. Stockham and Betz[9] found particles at the exhaust plane of a J57 engine operating at 75% normal power to have a number median diameter (N_g) of 0.053 μm and a geometrical standard deviation (σ_g) of 1.63. The number median diameter (N_g) can be converted to the mass median diameter (M_g) using[10]:

$$\ln M_g = \ln N_g + 3 (\ln \sigma_g)^2 \qquad (5)$$

For our example M_g equals 0.108

If we now divide the particle mass distribution into size intervals which represent 10% of the particle mass, we can calculate Stokes numbers and use Eq. (4) to determine N values for the mid-point particle diameter in each interval; Table 1 summarizes this procedure. In the particle-nozzle Stokes number calculation a gas viscosity (μ_g) of 358.3 μ poise, a probe inlet diameter (D_p) of 2.0 mm, and a particle density (ρ_g) of 1.0 gm/cm^3 were used.

With the computed N values (Table 1), Eq. (3) can be used to estimate average relative percent sampling errors ($(C-C_o)/C_o$ x 100)for subisokinetic operation ($U/U_o<1$) of an ARP 1179 smoke probe. Table 2 lists the computed values of C/C_o for the mid-point particle diameter of each 10% mass interval. In addition, Table 2 contains arithmetic average values of C/C_o for selected sampling velocity ratios (U/U_o) ranging from 0.1 to 0.7. When U/U_o is greater than 0.7 the sampling error is negligible. Figure 2 shows the averaged C/C_o and selected U/U_o values plotted as relative % error versus the % of the isokinetic condition. As shown in Figure 2, operation of an ARP 1179 smoke probe would produce an estimated 15-30% subisokinetic error at the assumed exhaust conditions.

SECTION IV

DISCUSSION

Under aircraft turbine engine smoke testing procedures as specified in SAE ARP 1179[2] the predicted subisokinetic sampling errors are not serious, since it has been shown by Champagne[11] that smoke filters which differ in collected particle mass by 50% can yield the same SAE smoke number. Thus, a smoke sample obtained isokinetically and a smoke sample obtained with U/U_o as low as 0.13 could produce identical smoke numbers. This can occur because smoke number is primarily influenced by the reflectivity of smaller particles on the filter paper. Larger particles will have little effect on the reading obtained, irrespective of their mass quantity. It must also be remembered that the error calculation was performed for a take-off engine power setting and therefore, must be considered a worst case analysis for a non-afterburning aircraft gas turbine engine.

The results are of special interest to those concerned with measuring the true smoke density (mass of particles/volume) of gas turbine engine exhausts. For this determination, especially at the take-off engine power setting, it is evident that subisokinetic sampling errors need to be considered. To insure representativeness, samplers should operate isokinetically or have a selection of sampling rates to maintain a sufficient U/U_o for all engine power settings.

SECTION V

SUMMARY

The recent aerosol sampling data reported by Martone et al[4] has been used to establish the validity of extending Zenker's[7] results to predict subisokinetic sampling errors in compressible flows. The prediction technique was applied to sampling gas turbine engine exhausts using an ARP 1179 smoke probe. The analysis shows that a smoke probe may produce a 15 to 30% subisokinetic sampling error at a take-off engine power setting. These errors do not greatly affect smoke number determinations but should be considered when true smoke density is measured.

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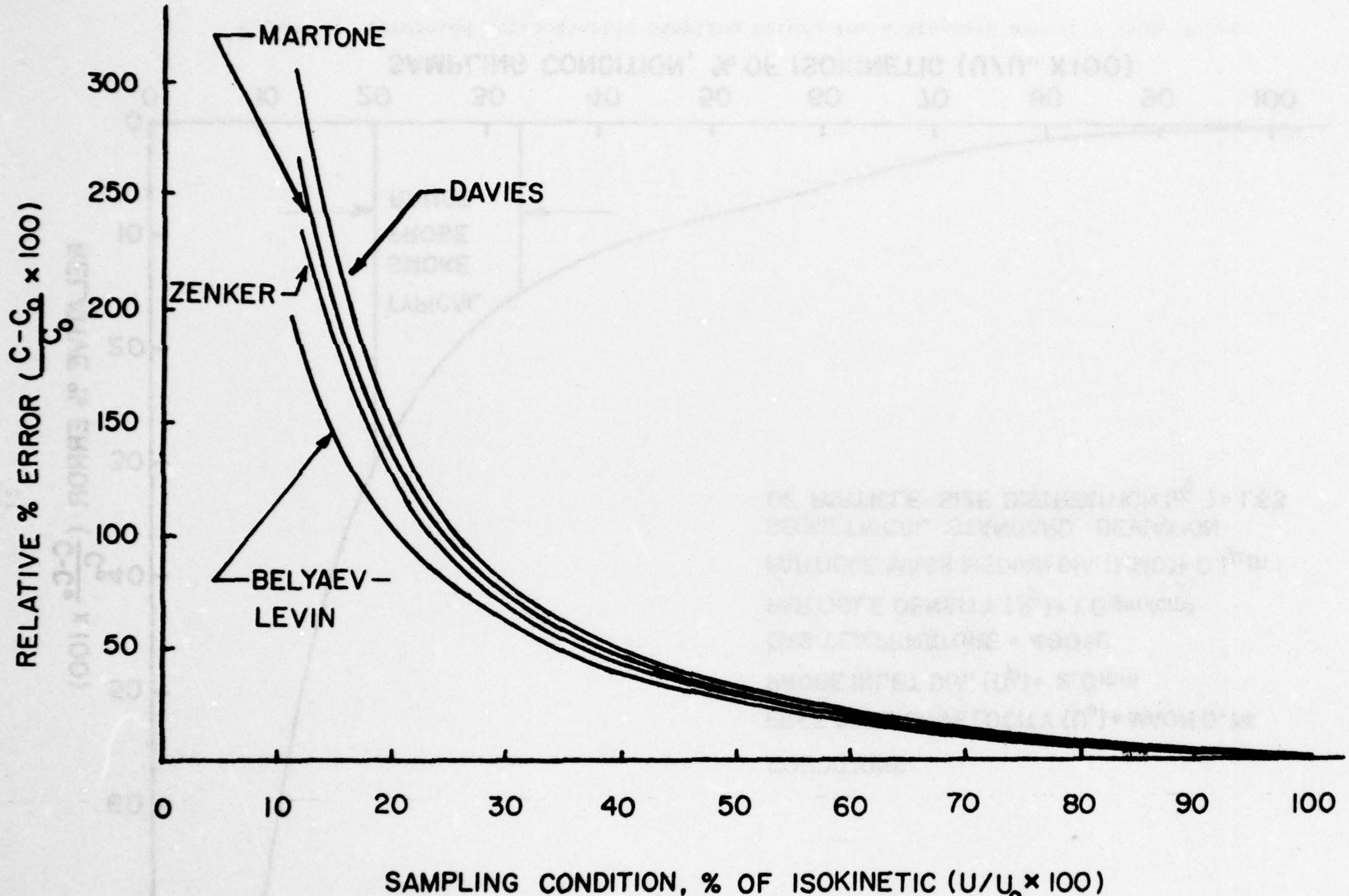

Figure 1. Comparison of Martone's[4] Results with the Results of Other Authors for a Stokes Number of 0.12

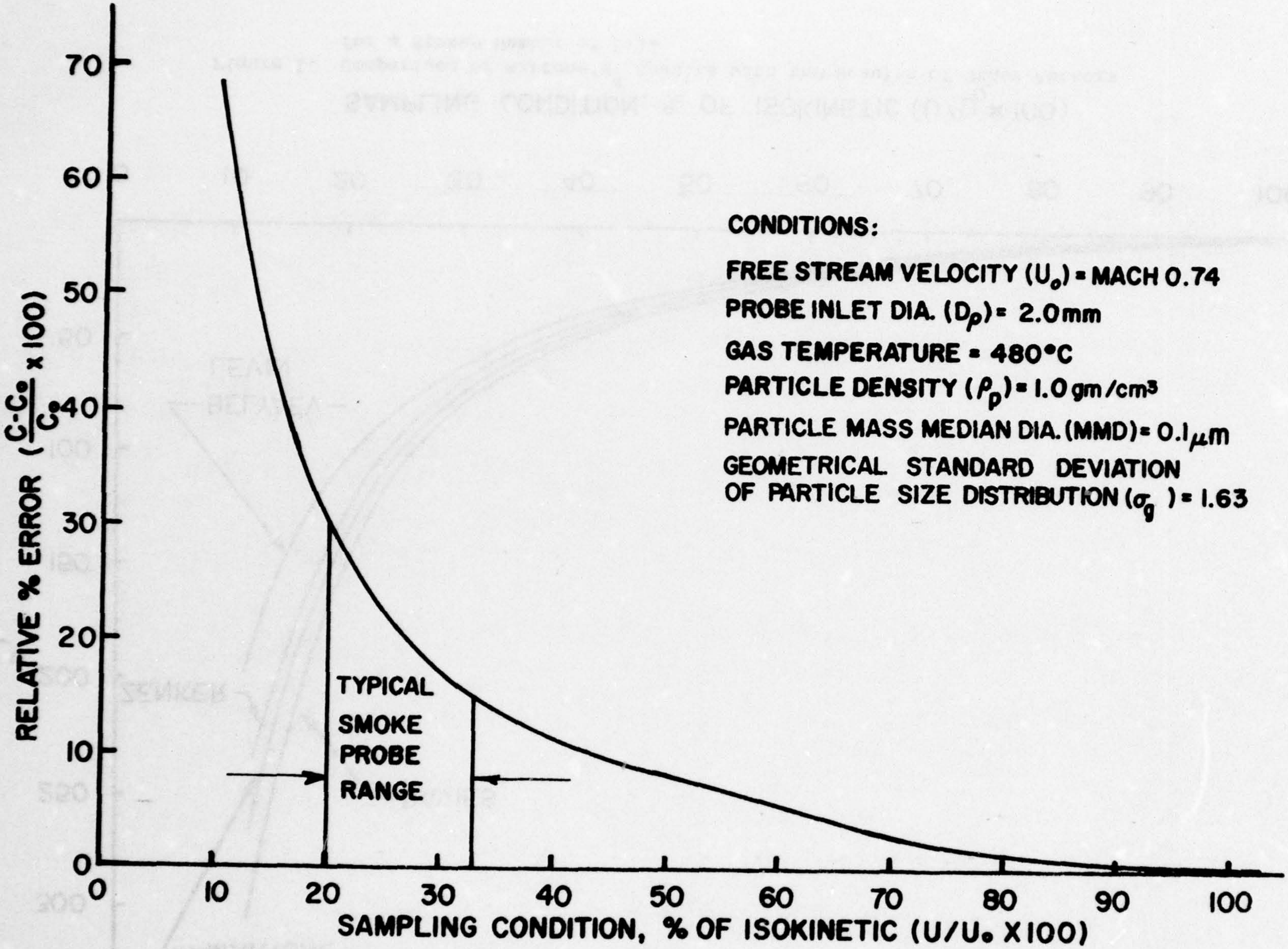

Figure 2. Predicted Subisokinetic Sampling Errors for a Standard ARP 1179 Smoke Probe

TABLE 1

STOKES NUMBERS (K) AND N VALUES FOR A TYPICAL GAS TURBINE ENGINE EXHAUST PARTICLE SIZE DISTRIBUTION

PARTICLE DIAMETER (μm)	WT% LESS THAN STATED DIAMETER	MID-POINT DIAMETER, d_p (μm)	Stokes Number K	N (Eq. 4)
0.023	0.1			
		0.040	0.0031	0.973
0.057	10			
		0.064	0.0052	0.959
0.070	20			
		0.077	0.0066	0.951
0.083	30			
		0.089	0.0078	0.945
0.095	40			
		0.102	0.0096	0.937
0.108	50			
		0.115	0.010	0.935
0.121	60			
		0.131	0.013	0.923
0.140	70			
		0.152	0.017	0.909
0.163	80			
		0.183	0.021	0.897
0.202	90			
		0.351	0.060	0.812
0.500	99.9			

TABLE 2

PREDICTED AEROSOL CONCENTRATION RATIOS (C/C_o) FOR SELECTED SAMPLING VELOCITY RATIOS (U/U_o)

PARTICLE DIAMETER, d_p (μm)	AEROSOL CONCENTRATION RATIO, C/C_o				
	$U/U_o = 0.7$	$U/U_o = 0.5$	$U/U_o = 0.3$	$U/U_o = 0.2$	$U/U_o = 0.1$
0.040	1.01	1.03	1.06	1.11	1.24
0.064	1.02	1.04	1.10	1.16	1.37
0.077	1.02	1.05	1.11	1.20	1.44
0.089	1.02	1.06	1.13	1.22	1.50
0.102	1.03	1.06	1.15	1.25	1.57
0.115	1.03	1.07	1.15	1.26	1.59
0.131	1.03	1.07	1.18	1.31	1.69
0.152	1.04	1.09	1.21	1.36	1.82
0.183	1.04	1.10	1.24	1.41	1.93
0.351	1.08	1.19	1.44	1.75	2.69
AVE C/C_o	1.03	1.08	1.17	1.30	1.68

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